CHAPTER 19

DIRECT CURRENT MOTORS

INTRODUCTION

Although more expensive and difficult to maintain than AC motors, DC motors have been extensively used on shipboard because they had a great advantage where precise speed control and varying loads are concerned. Direct current is better suited to handle the various cargo-handling winches and capstans. Speed and torque requirements are precise and dependable.

In all important aspects, DC motors are identical to DC generators. Their construction and operating principles, as discussed in Chapter 18, are interchangeable. Many manufacturers make DC machines for use either as a DC motor or DC generator. The main differentiating factor between the motor and the generator is what the marine engineer must electrically control. The engineer must control what comes out of the generator and what goes into the motor. As with generators, the major classes of DC motors are –

- Shunt wound.
- Series wound.
- Compound wound.
- Separately excited.

These types of motors differ only in the connection of the field circuits (Figure 19-1). The armatures, commutators, and so forth are nearly identical with each other and with those of the generators. All four major classes of motors are widely used. This is in contrast to the generators, in which the compound wound type is used for nearly all general power applications.

PRINCIPLE OF DC MOTOR ROTATION

The operation of a DC motor depends on the attraction and repulsion principles of magnetism. When current is supplied to the field poles of a motor, the field poles turn into electromagnets. If a two-pole machine is used, north and south polarities are established toward the center of the machine.

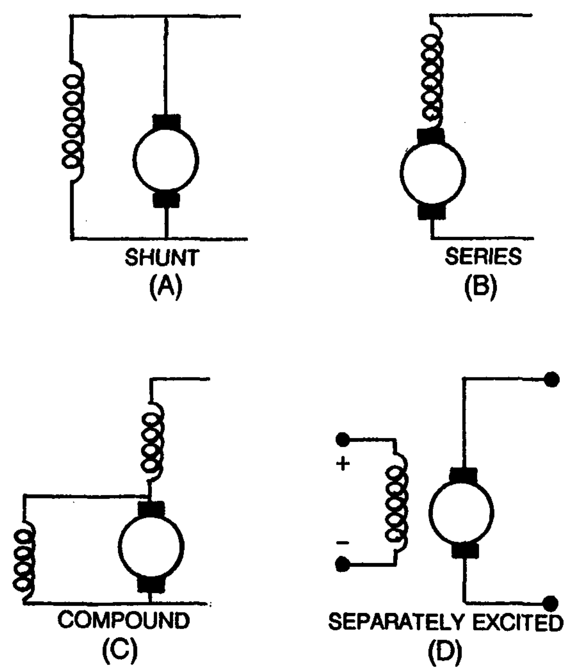

FIGURE 19-1. Schematic Diagrams of DC Motors.

Figure 19-2 view A shows how the two field poles are wound to produce the opposite magnetic effect. The magnetic lines of force, between these two unlike magnetic poles, establish a direction of movement from the north polarity to the south polarity. By themselves, these lines of force from the field poles cannot do anything to force the motor's armature to rotate.

If current is supplied from the generator through the motor's brushes and commutator to the armature windings, a magnetic field results around the armature windings (view B). DC motor torque depends on the principle that a current-carrying armature conductor has a magnetic force encircling it. These lines of force are determined by the left-hand rule for conductors. You can determine these lines of force when you know which direction the current flows through the conductor. If you visualize yourself grasping the insulated conductor in your left hand with your thumb extended in the direction of current flow, negative (-) to positive (+), your fingers will point in the direction of the magnetic lines of force. Figure 19-3 illustrates this point.

The current entering the motor armature windings and the magnetic lines of force that result around the armature windings interact with the magnetic lines of force from the field poles. Torque is produced in proportion to the current in the armature windings. The greater the armature current, the greater the motor torque. Additionally, the direction of current flow through the armature and the polarity of the field poles determine the direction that the armature will revolve.

Figure 19-4 shows the lines of force established around the armature coils. The cross signifies the current from the generator's negative terminal moving away from us into the motor armature. The dot represents the current moving toward us (and toward the positive generator terminal) in the motor armature. The left-hand rule establishes the lines of force around these armature conductors.

The two field poles show their magnetic lines of force establishing a direction from north to south (left to right). The armature conductor magnetic lines of force are circular and are determined by the current direction. The following outline describes the combining of the current-carrying

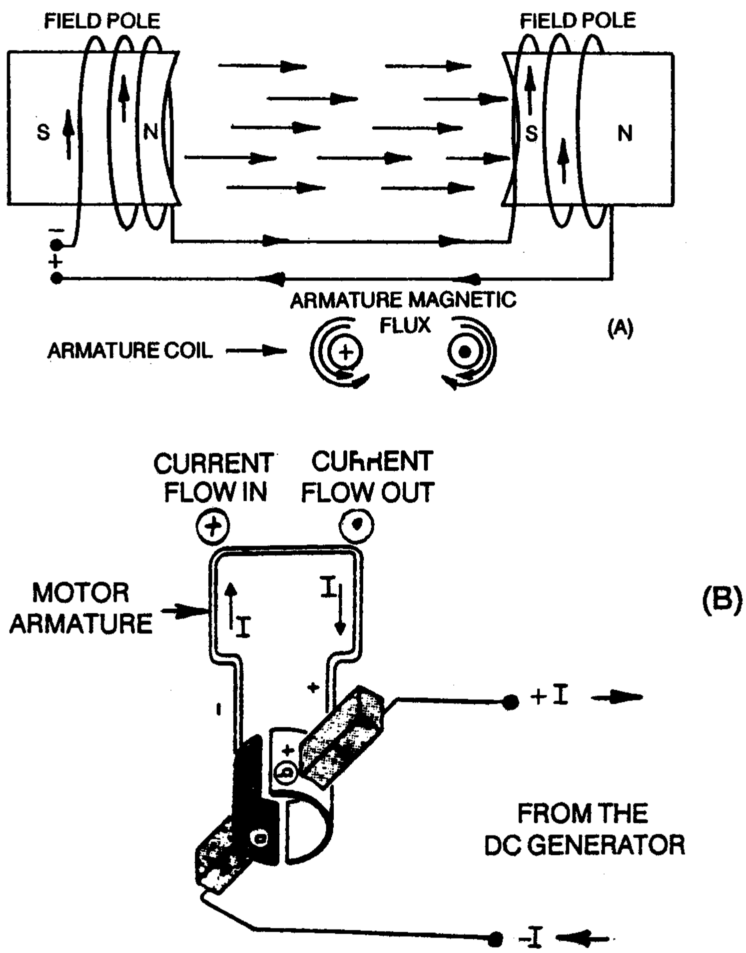

FIGURE 19-2. Lines of Force in the Magnetic Field.

armature magnetic lines of force with the field pole magnetic lines of force:

- The circular lines of force in the cross conductor and the magnetic lines of force from the field poles effectively cancel out each other directly above the cross conductor.
- The circular lines of force below the cross conductor work with or add to each other's magnetic lines of force. In this way, the additive force below the cross conductor forces the conductor up through the canceled lines of force directly above it.
- The circular lines of force developed from the dot conductor effectively cancel the magnetic lines of force from the field poles directly below the dot conductor.
- The circular lines of force directly above the dot conductor add to the magnetic lines of force from the field poles. In this manner, the dot portion of the armature is moved down.

Since both the cross and the dot conductors are connected together and rotate at the center, the armature starts to turn. This turning force developed from the magnetic lines of force is known

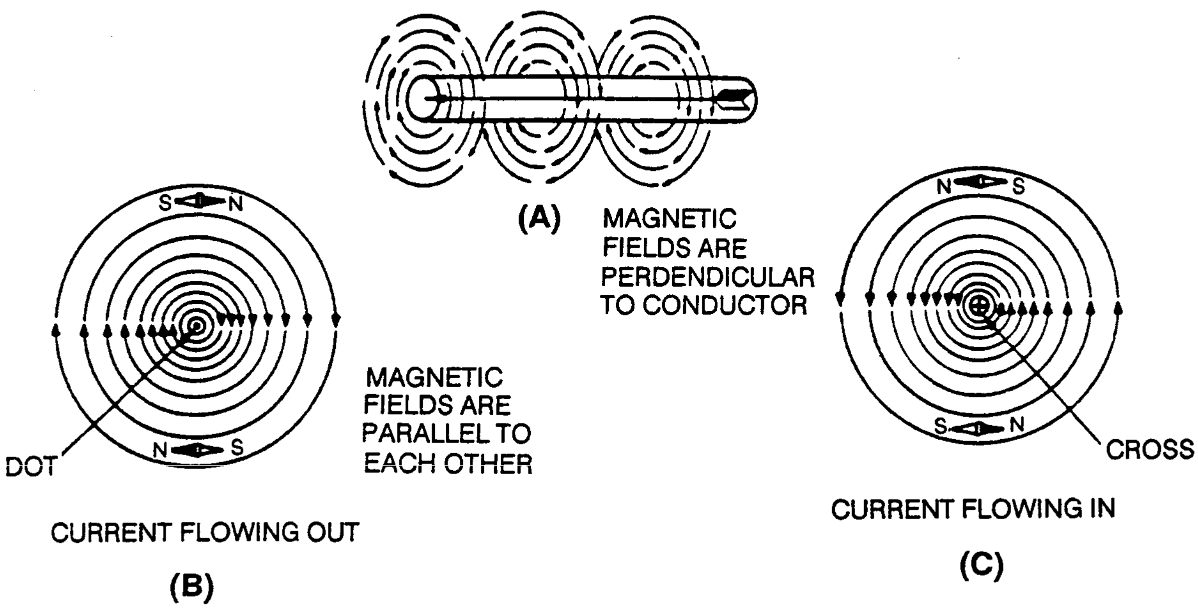

FIGURE 19-3. Magnetic Lines of Force Surrounding a Current-Carrying Conductor.

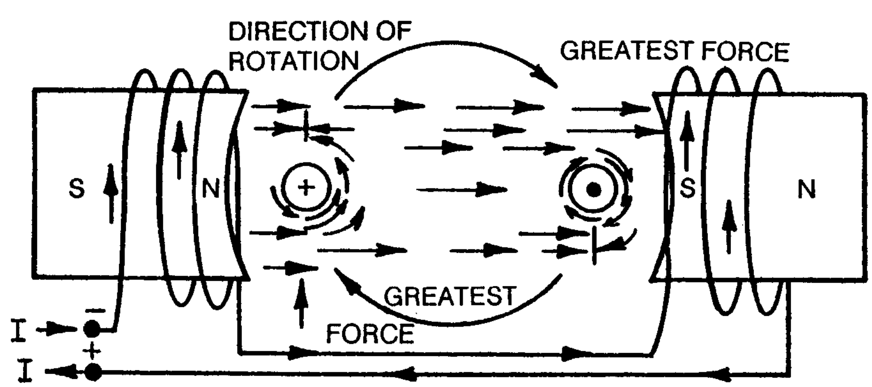

FIGURE 19-4. Combined Armature and Field Magnetic Lines of Force.

as torque. The amount of torque developed depends primarily on the current through the armature.

COUNTER EMF

Any time a conductor is moved in a magnetic field, an EMF is produced. When this occurs in a motor as a by-product of motor torque, the EMF is called counter EMF. This is because the EMF produced in the motor opposes the EMF of the generator. To distinguish between the two EMFs, the term "counter EMF" is applied to every component that is not a prime distribution system power-generating device. The ship service generator, battery systems, and the emergency generator are EMF-designated devices.

Counter EMF is directly proportional to the speed of the armature and the field strength. That is, the counter EMF is increased or decreased if the speed is increased or decreased, respectively. The same is true if the field strength is increased or decreased.

Counter EMF is a form of resistance. Any resistance opposes and reduces the current. The greater the CEMF, the less current delivered to the motor armature. When the motor is first started, during that infinitesimal moment when the armature has not yet begun to turn, armature CEMF is at zero. Maximum current is available from the generator to the motor armature because the only resistance is in the motor wire.

CEMF is produced in the motor armature as it begins to turn. The faster the armature turns, the more CEMF is generated. This counter EMF reduces the current from the ship service generator. Table 19-1 is a comparison of the armature speed, CEMF, motor armature current, and resulting motor torque for normal motor operations.

The CEMF restricts the current flow. When current in the motor armature is reduced so is the motor's torque. Since CEMF is proportional to the speed of a motor and current is indirectly proportional to CEMF, a motor automatically adjusts its speed to corresponding changes in load. When the motor's RPM decreases because of an increase in load, the CEMF is reduced, and current increases. The increased current produces greater torque, and the motor increases its RPM.

TABLE 19-1. Normal DC Motor Operation Comparisons.

	START UP	NORMAL OPERATION	INCREASING LOAD
Motor Armature Speed (RPM)	Zero	Highest	Decreasing
CEMF	Zero	Highest	Decreasing
Armature Motor Current	Highest	Lowest	Increasing
Motor Torque	Highest	Lowest	Increasing

All our DC motors conform to Table 19-1. They will deviate only in the specific characteristics of that motor's individual design. For example, all torque is increased when the armature moves slowly. In the series motor, however, its design produces an unusually high value of motor torque. This becomes the characteristic of the series motor.

A motor is not designed to operate at the excessive current levels exhibited when it is first started. If the motor were unable to increase in speed because it was too heavily loaded, sufficient CEMF would be unavailable to reduce the generator's current. This excessive current would shortly burn out the motor. A motor must be allowed to come up to its rated speed rapidly.

ARMATURE REACTION

There are individual magnetic lines of force from the field poles and the armature. Magnetic fields tend to combine. Additionally, the magnetic lines of force are distorted (or concentrated) by an iron core. Figure 19-5 shows the field flux (view A) and the armature flux (view B) individually. View C shows the distortion caused by the interaction of the two fields and the armature core movement. This distortion is known as armature reaction.

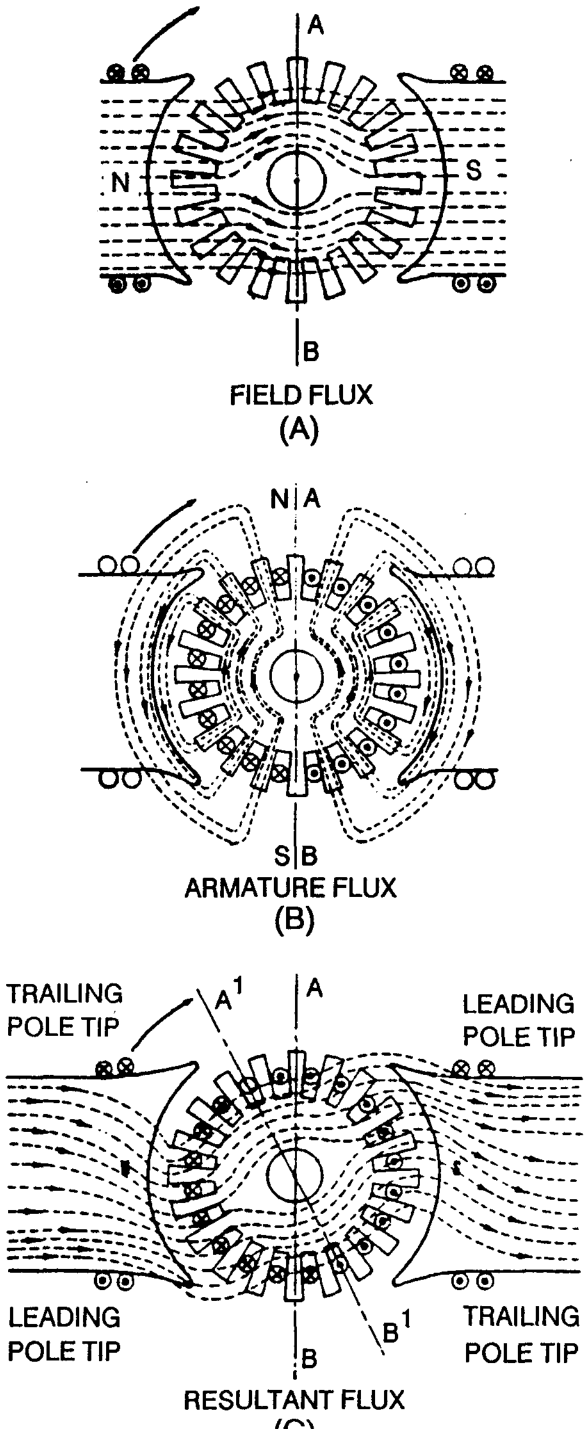

FIGURE 19-5. Armature Reaction in a Motor.

The armature current in a generator flows in the same direction as the generated EMF, but the armature current in a motor is forced to flow in the opposite direction to that of the CEMF. In a motor, the main field flux is always distorted in the opposite direction to armature rotation (view C); whereas in a generator, the main field flux is always distorted in the same direction as armature rotation. The resultant field in the motor (view C) is strengthened at the leading pole tips and weakened at the trailing pole tips. This action causes the neutral plane to shift to A'B'.

The armature reaction is overcome in a motor by the same methods used in the generator; that is, by the use of laminated pole tips with slotted ends, interposes, and compensating windings. In each case, the effect produced is the same as the results produced in the generator, but it is in the opposite direction.

To further ensure successful commutation, small slots on the brush rigging permit a slight brush position adjustment. By placing a tachometer on the motor shaft, an indication of motor efficiency may be obtained. Adjust the brush position for the fastest armature rotation in the absence of sparking.

SHUNT WOUND MOTOR

The shunt wound motor is used where uniform speed, regardless of load, is wanted. It has reasonably good starting torque but is not suited for starting very heavy loads. It is therefore used where the starting load is not too heavy, as in blowers, or where the mechanical load is not applied until the motor has come up to speed. It is essentially a constant speed machine.

The shunt motor is electrically identical with the shunt generator diagramed in Figure 19-6. It is considered a constant speed machine because speed does not ordinarily change more than 10 to 15 percent within the load limits.

The field pole circuit of a shunt motor is connected across the line and is thus in parallel with the motor armature. Both the motor armature and the shunt field are in parallel with the switchboard bus. If the supply voltage is constant, the current through the field pole coils and consequently the magnetic field will remain constant. The resistance in the field pole coils will change little. Hence, the current in the field poles will remain virtually constant. On the other hand, the resistance in the armature will change as the CEMF increases and decreases. This means that the current in the armature will vary inversely with the CEMF.

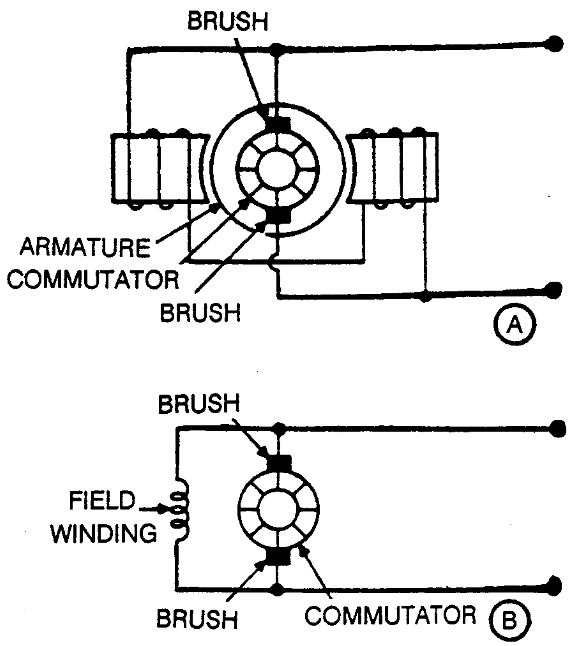

FIGURE 19-6. Shunt Motor Diagram.

When there is no load on a shunt motor, the only torque necessary is that which is required to overcome friction and windage. (Windage is a mechanical loss due to the friction between the moving armature and the surrounding air.) The rotation of the armature coils through the field pole flux develops a CEMF. The CEMF limits the armature current to the relatively small value required to maintain the necessary torque to run the motor at no load.

When an external load is applied to the shunt motor, it tends to slow down slightly. The slight decrease in speed causes a corresponding decrease in CEMF. If the armature resistance is low, the resulting increase in armature current and torque will be relatively large. Therefore, the torque is increased until it matches the resisting torque of the load. The speed of the motor will then remain constant at the new value as long as the load is constant. Conversely, if the load on the shunt motor is reduced, the motor tends to speed up slightly. The increased speed causes a corresponding increase in CEMF and a relatively large decrease in armature current and torque.

The amount of current flowing through the armature of a shunt motor depends on the load on the motor. The larger the load, the larger the current. Conversely, the smaller the load, the smaller the current. The change in speed causes a change in CEMF and armature current in each case.

No Field Condition

In order for a DC motor to turn, there must be the magnetic lines of force from the armature and the magnetic lines of force from the field poles. As shunt motors age and corrosion becomes a problem, a runaway condition may present itself. When the shunt field is opened and current is available only to the armature, the motor speed will increase dangerously.

It would seem that without the shunt field the motor would stop. However, the large metal pole shoes of the DC machine support a fairly substantial residual magnetic field. This residual magnetism is just enough to ensure that the magnetic principles that sustain the armature movement are present.

The residual magnetic field is not, however, substantial enough to develop a suitable CEMF in the armature. Without the proper proportion of CEMF, current flow to the armature increases. The more current to the armature, the greater the torque and the faster the damaged shunt motor rotates. A no field release is employed by shunt motors to prevent such a casualty. When the shunt field is de-energized, the no field release disconnects the motor from the circuit.

Speed Control

The magnetic field from the shunt motor field poles is necessary to maintain an adequate CEMF in the motor armature. As long as the CEMF is maintained, the current to the armature is restricted, and the motor operates at its rated speed.

Above Normal Speed Control. DC motors with shunt fields (both shunt and compound motors) can control the speed above a certain operating (or base) point. This is called speed control above normal speed. Figure 19-7 shows a shunt motor with full field resistance. A rheostat in series with the shunt field will determine the amount of resistance in the shunt field. The greater the resistance in the shunt field, the less current will enter the shunt field. The reduced current in the shunt field means that the magnetic field has been reduced. With a reduction in magnetic field, there is a reduction in armature CEMF. When the CEMF is reduced, the motor armature receives more current. The more current in the armature, the greater the torque developed. Therefore, motor speed increases.

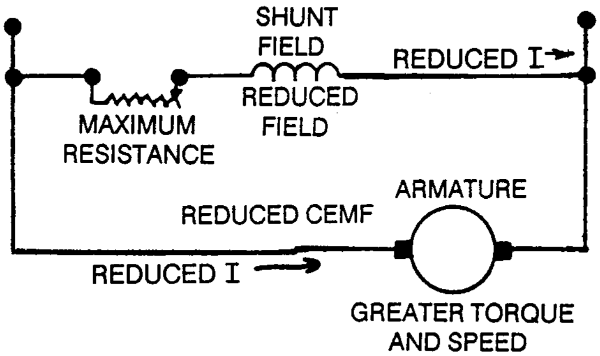

FIGURE 19-7. Shunt Motor With Full Field Resistance.

Below Normal Speed Control. To reduce the speed of the shunt or any DC motor, it is necessary to reduce the current to the armature. A rheostat in series with the armature will increase the resistance in the armature circuit or decrease the resistance in the armature circuit. As armature resistance is increased, current to the armature is decreased. The decrease in armature current decreases the torque and armature speed. Control of the armature circuit in this manner does not substantially affect the CEMF created from the rotating armature conductors within the field poles' strong magnetic field.

Use of Shunt Motors

The speed of a shunt motor remains nearly constant for a given field current. The constant speed characteristic makes the use of shunt motors desirable for driving machine tools or any other device that requires a constant speed driving source.

SERIES WOUND MOTOR

Where there is a wide variation in load or where the motor must start under a heavy load, series motors have desirable features not found in shunt motors. The series wound motor is used where high starting torque and varying speed is desired. The armature and the series field are connected in series. With high armature and field currents, it has a very high starting torque and is well suited for starting heavy loads such as the diesel engines.

Figure 19-8 illustrates the series motor. Notice that the series field is in series with the armature windings. When the motor is first started, with the negligible effects of the CEMF, current flow through the armature is high. Since the armature and the series field are in series, the current in the armature is the same current through the series winding. TM large current develops a very strong magnetic field and results in an extremely high torque. Conversely, if the motor is operating at rated speed, the CEMF will be very high, and the current in the series field winding and armature is reduced proportionally. This means that the series motor can develop a very high torque and respond to increases in loading (reductions in armature RPM) rapidly.

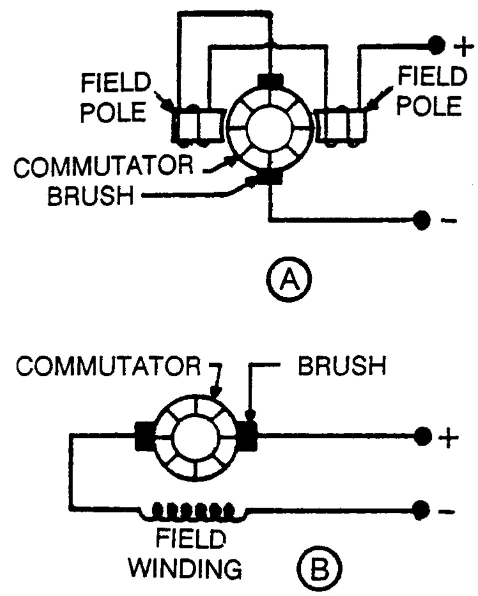

FIGURE 19-8. Series Wound Motor.

Series Motor Speed

The series motor will continue to increase in speed as long as there is more torque developed than is necessary to turn the load. This additional torque is called acceleration torque.

When a series motor is heavily loaded, it slows and produces more torque. As the load is removed, the motor increases in speed. If the load is suddenly removed from the series motor, the accelerating torque is just enough to continue to increase the motor's speed. The continuously increasing speed can destroy the motor.

No-Load Operation

With the load removed and armature speed increasing, CEMF should also increase. However, CEMF is a by-product of a conductor moving in a magnetic field. The series motor field varies with armature current, and CEMF decreases as the field decreases.

There is sufficient CEMF to reduce current to the armature, but in doing so, CEMF also limits the current to the series field pole windings. The series field still passes enough current to overcome windage and friction and develop an accelerating torque. However, at a reduced current flow, there is not enough of a magnetic field established to generate a proportional CEMF at these reduced current levels. Even though CEMF increases as speed increases, the overall reduction of current through the series field winding makes it impossible for a magnetic field to produce the CEMF necessary to eliminate the acceleration torque. Due to internal losses, the CEMF will always be overcome by the EMF in a branch circuit. After all, the EMF from the power supply was essential to the creation of the CEMF. The difference between the shunt field and the series field is that the shunt field current is not changed by the armature current.

When the load is removed from the series motor, enough current and accelerating torque is available to exceed the feeble CEMF. Armature RPM increases endlessly.

To prevent the series motor from overspeeding and destroying itself, many series motors are provided with a small shunt field to maintain adequate CEMF if the load is accidentally removed from the motor.

COMPOUND MOTORS

Compound motors, like compound generators, have both a shunt and a series field. In most cases, the series winding is connected so that its magnetic field aids that of the shunt winding magnetic field (Figure 19-9 view A). The current entering both the series field and the shunt field is moving in the same direction. Both fields produce the same magnetic field and aid each other. Motors of this type are called cumulative compound motors. In the cumulative motor, the speed decreases (when a load is applied more rapidly than it does in a shunt motor, but less rapidly than in a series motor. The cumulative compound motor is used where reasonably uniform speed combined with good starting torque is needed.

The differential compound motor is used only for low power work. Figure 19-9 view B shows the opposing magnetic fields of the differential compound motor. Notice that the series winding's magnetic field is connected to oppose the shunt winding's magnetic field. The differential compound motor maintains even better constant speed, within its load limit, than the shunt motor. But it has very poor starting torque and is unable to handle serious overloads.

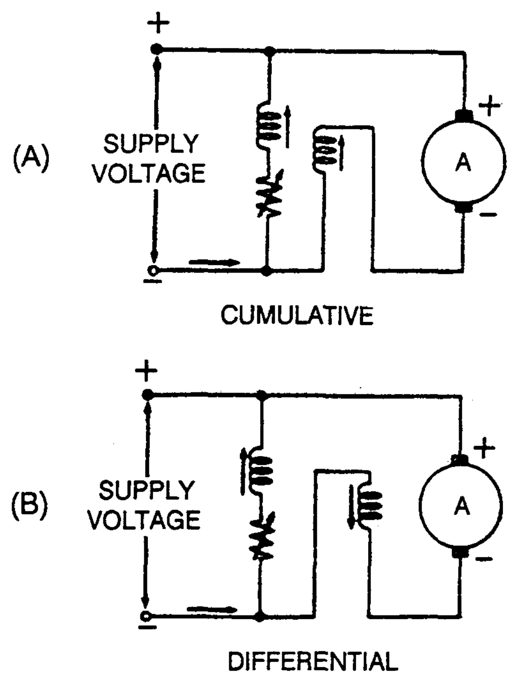

FIGURE 19-9. Types of Compound Motors.

SEPARATELY EXCITED MOTOR

Figure 19-10 shows the separately excited DC motor. This circuit diagram shows an individual armature circuit and an individual field circuit. A DC power source that is not armature-connected supplies power to the field poles. Notice the variable resistors for speed control. The armature rheostat controls speeds below the normal base speed, and the rheostat in the separately excited field controls speeds above the rated base speed. Separately excited motors are not commonly found in the Army marine field.

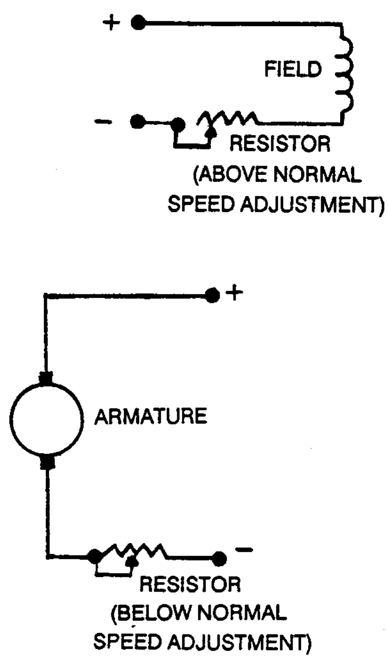

FIGURE 19-10. Separately Excited DC Motor.

DC MOTOR ROTATION REVERSAL

The direction in which the DC motor armature will rotate depends on two conditions:

- The direction of the magnetic lines of force from the field poles.
- The direction of the current through the armature windings and the resulting armature lines of force.

The section on the principle of DC motor rotation at the beginning of this chapter discussed how the lines of force from the field poles and the current-carrying armature conductors interacted to produce torque. To change the direction of armature rotation, it is necessary only to change the two fields' relationship. In practice, it is unimportant what magnetic field is changed as long as their relationship is changed.

Figure 19-11 view A shows an armature turning in a clockwise direction. By changing the direction of current through the armature alone (Figure 19-11 view B), the magnetic lines of force from the armature react differently to the field pole lines of force. The armature now moves in the counterclockwise direction. Any interposes or compensating windings must also maintain the same current direction as the armature windings to effectively eliminate the armature reaction caused by armature current. However, the shunt and/or series fields must not be changed.

The motor rotation can also be changed by reversing the current through the field poles alone. If the motor is a compound motor, then both the series and shunt fields must have their current flow reversed. The current flow in the armature must be maintained in the original direction.

The motor direction cannot be changed by reversing the polarity of the incoming power lines. Figure 19-11 view C shows the armature rotating in a clockwise direction. When the incoming power line polarities are reversed, the motor still rotates in the same direction. Although the field pole polarity and the armature conductor current flows have reversed, the relationship between the fields in view A and view C have not changed. As long as the relationship between the field pole magnetic lines of force and the armature magnetic lines of force remain unchanged, the direction of rotation will not change.

MOTOR BRAKING

Electromechanical Braking

Hoists are equipped with ordinary friction brakes so that cargo loads can be stopped exactly when and where desired. Friction brakes, like those found on the automobile, are an asbestos and metallic material that is pressed against a metal drum connected to the motor armature or winch drum. The friction between the brake pads and the drum bring the motor armature speed rapidly under control. Since the point where braking is to take place is usually remote from the operator, the brakes are usually mechanically applied and electrically released. When electrical power is not applied to the brake system, springs hold the friction brake and drum securely. Energizing a solenoid provides a magnetic field that overcomes the spring pressure, and the brake is released. This arrangement follows a fail-safe principle employed on winches and capstans. If a power failure should occur with a load hoisted, the load could otherwise drop, damaging the cargo and endangering anyone working nearby. Instead, the power failure would de-energize the solenoid, and the spring pressure would again be applied to the brake drum. A friction brake is very effective at moderate and slow speeds.

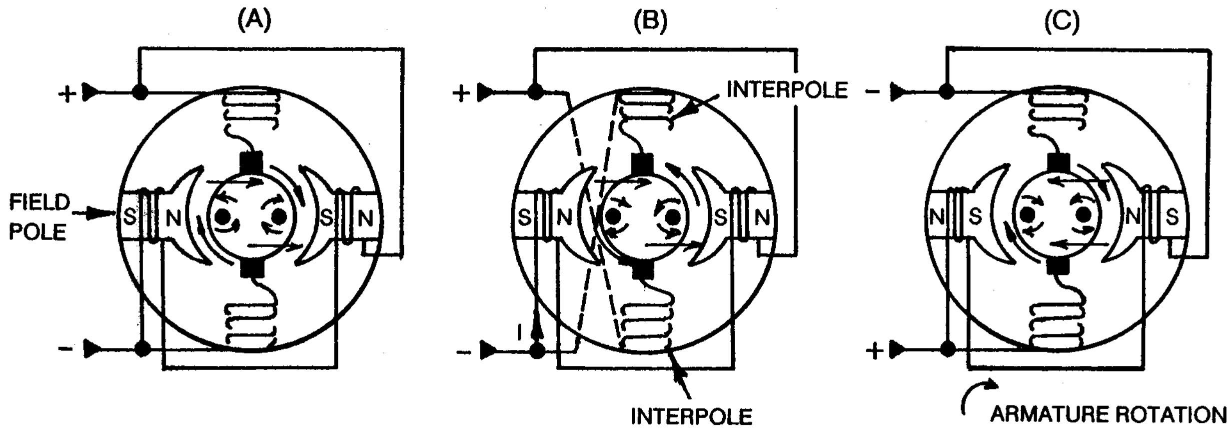

FIGURE 19-11. Reversing DC Motors.

Dynamic Braking

Depending on the motor application, either friction braking alone or in conjunction with dynamic braking can be used. There are only minor differences between generators and motors. A voltage applied to a generator will produce torque. Similarly, when a motor is mechanically turned, it will produce an EMF. Dynamic braking takes advantage of the similarities (Figure 19-12).

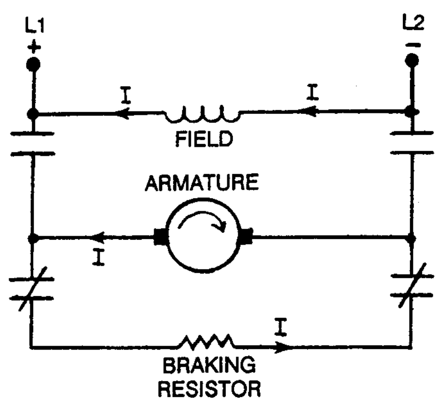

FIGURE 19-12. Dynamic Braking Circuit.

Any motor will stop eventually when power is disconnected. To decrease the armature speed rapidly, the motor is reconnected as a generator. The field poles maintain their excitation from the normal line voltage.

When the STOP button is pressed, the friction brake is applied. At high armature speeds, the friction brake is inefficient and would bum out after a few applications. To prevent this, only the armature of the motor is disconnected from the line voltage. The armature conductors are rapidly turning in the magnetic field of the field poles. Through external switches, a complete path has been provided through the armature and brush assemblies and connected to a braking resistor. As the armature conductors cut the lines of force from the magnetic field poles, the armature produces an EMF. Since there is a completed electrical circuit, a current flow exists in the armature. The magnetic lines of force from the armature current interact with the lines of force from the field poles in a way that opposes the rotation of the armature. The faster the armature moves, the greater the generated EMF and resulting opposing armature magnetic field. The greater the armature speed, therefore, the greater the slowing ability of the motor. As armature speed reduces, so does the generated EMF. A motor cannot be stopped with dynamic braking; it can only be slowed. Dynamic braking is exceptionally well suited for rapidly slowing fast-moving armatures. Together, dynamic braking and the friction brake provide an effective way to manage motor armature and winch speeds.

For additional information on the inspection, testing, troubleshooting, and overhaul of DC machines, refer to TM 5-764, *Electric Motor and, Generator Repair,* dated September 1964.

NOTE: The current developed in the armature during dynamic braking is applied to a resistor bank (braking resistor), and the power is consumed as heat.